The effect of ship accelerations on three-dimensional low back loading during lifting and pulling activities

Kingma, Idsart; Delleman, Nico J.; Van Dieën, Jaap H.

published in
International Journal of Industrial Ergonomics
2003

DOI (link to publisher)
10.1016/S0169-8141(03)00029-5

International Journal of Industrial Ergonomics 32 (2003) 51–63

International Journal of Industrial Ergonomics

www.elsevier.com/locate/ergon

The effect of ship accelerations on three-dimensional low back loading during lifting and pulling activities

Idsart Kingma[a,*], Nico J. Delleman[b], Jaap H. van Dieën[a]

[a] Faculty of Human Movement Sciences, Institute for Fundamental and Clinical Human Movement Sciences, Vrije Universiteit, Van der Boechorststraat 9, Amsterdam, The Netherlands
[b] TNO Human Factors, Soesterberg, The Netherlands

Received 12 November 2002; received in revised form 6 February 2003; accepted 7 February 2003

Abstract

Manual materials handling on a moving platform, like a ship, might be a risk factor for the development of low back pain due to the influence of accelerations on low back loading. In the current simulation study, 3-D accelerations, measured on a frigate were applied to the kinematics of symmetrical and asymmetrical lifting movements and to a pulling task that had been performed under stable conditions. The aim was to find out to what extent low back loading is increased when the task execution is not adapted to the ship accelerations.

Unfavorable timing, analyzed using the 99th percentile of predicted low back moments, resulted in only a moderate (up to 15%) increase of extending and total low back moments, and in a substantial increase of the twisting moment (up to 67%) during asymmetrical lifting. Moments in the pulling task were low and were relatively unaffected by ship accelerations, but adaptation of the movement pattern to prevent falling would be needed more often than during lifting. It furthermore appeared that a substantial reduction of low back loading by favorable timing is not a realistic option. Designing tasks in such a way that they are located midship would reduce the 99th percentile of predicted low back moments. During lifting, orienting the task in such a way that the feet are pointing sideward relative to the ship reduces the predicted peak twisting moment at the low back compared to pointing the feet forward or backward.

Relevance to industry

Accelerations on a ship may influence safety and loading of workers during manual materials handling. This study investigates potential effects of moderate accelerations on low back loading during lifting and pulling tasks. It is shown that working midship reduces the risk of low back overloading, compared to working at the front deck.

Keywords: Biomechanical modeling; Lifting; Pulling; Low back load; Acceleration; Ship

1. Introduction

Ship motion is known to affect human performance in several ways. General factors like motion sickness or fatigue due to increased energy requirements can reduce human capacity (Wertheim, 1998). Furthermore, biomechanical factors can increase the difficulty of certain tasks, increase joint loading, or challenge whole body balance control. For a population of fishermen the year-prevalence of musculoskeletal problems was

*Corresponding author. Tel.: +31-20-4448492; fax: +31-20-4448521.

E-mail address: i_kingma@fbw.vu.nl (I. Kingma).

0169-8141/03/$ - see front matter
doi:10.1016/S0169-8141(03)00029-5

reported to be 74% (Törner et al., 1988). The majority of the complaints (70%) were related to the low back. In addition, 49% stated that these symptoms had necessitated medical consultation and 55% had been on sick leave for this reason. Lifting activities and ship motions were reported as the main causes of severe workload (Törner et al., 1988).

It seems reasonable to assume that ship motion is one of the factors that contribute to the occurrence of low back pain in workers doing physical work on board of a ship. On the other hand, it might be argued that experienced seamen could take advantage of ship accelerations in order to reduce low back loading. For instance, the peak extension moment in the low back, required to lift a load from the deck, would reduce if the upward lifting movement is initiated during a downward ship acceleration. Likewise, horizontal ship accelerations might reduce low back loading in a pulling task during upright stance. However, the acceleration of a ship is not uni-directional. Accelerations in upward–downward, forward–backward and sideward direction occur simultaneously and may not be strongly correlated. Thus a possible reduction in low back load due to downward acceleration could be offset by accelerations in the perpendicular plane, possibly also leading to elevated lateral flexion- and twisting moments at the low back.

Thus, it remains uncertain whether it is possible to reduce low back loading on ships by adequate timing of force exertions like lifting and pulling. In the current study, 3-D accelerations measured on two locations at a frigate of the Royal Netherlands Navy were used. To evaluate the effect on low back loading these accelerations were added to symmetric and asymmetric lifting movements and to a rope-pulling task that were executed under laboratory conditions. Hence, the effect of ship accelerations on 3-D low back loading during lifting and pulling was simulated. Furthermore, it was examined whether those tasks could be performed in the same way as they are performed under normal conditions, i.e., without the need to adapt the movement pattern to prevent falling.

The aim was to find out to what extent unfavorable timing can lead to elevation of the 3-D low back loading when the task execution is not adapted. In addition, it is investigated whether it is theoretically possible to time the tasks on a ship in such a way that low back loading is reduced. Furthermore, the location on the ship and the orientation of the worker with respect to the ship during lifting and pulling (with the feet pointing forward, sideward or backward) might influence the effect of ship accelerations on low back loading. For that reason, the effect of subject orientation and the effect of the location of the subject on the ship are also investigated in this simulation study.

2. Methods

The current study assumes that the kinematics of subjects performing lifting and pulling movements under normal conditions can be considered representative for the kinematics relative to the deck of the ship during lifting and pulling activities on board of a ship. It is realized, however, that the assumptions in the current simulation imply a simplification of the actual situation and can only be valid for light to moderate accelerations, where posture adaptations to preserve balance, are not strictly needed. Ship accelerations were measured on board of a 120 m frigate under two sea-state conditions, sailing at two angles relative to the waves. The effect of these accelerations on low back loading was estimated by applying these ship accelerations to the kinematics of six subjects performing two lifting tasks and a pulling task that had been performed on a stationary support surface. Because of the large size of the ship, angular accelerations were considered negligible. However, angular changes of the ship did cause substantial effects in terms of a projection of the gravity vector on the local horizontal axes of the ship. Those effects were taken into account in the horizontal components of the measured accelerations of the ship.

2.1. Subjects and procedure

After signing an informed consent, six healthy young males (average $\pm$ SD: age 24.3 ± 3.3 yr, weight 77.1 ± 15.2 kg, height 183.5 ± 9.5 cm) participated in the laboratory experiment. The subjects performed three tasks: one asymmetrical and one symmetrical lifting movement and a rope-pulling task. A 428 × 348 × 238 mm (width × depth × height) box was used for the lifting movements. The box weighed 15 kg and the handles were at 210 mm height. For the symmetrical lifting movement, the box was placed 5 cm in front of the toes. For the asymmetrical lifting movement, the starting position of the box was rotated 30° to the right of the subject and placed at a distance of 5 cm from the edge of the right foot. The lifting movements started and ended in symmetrical upright standing posture. The lifting technique was a leg technique: subjects were asked to bend their knees while lifting the box. For the rope-pulling task, a 30 kg weight was used. The subjects were asked to pull this weight slowly upward through a rope-and-pulley construction. The pulley was placed at the height of the shoulder joints, so that the subjects exerted an almost horizontal force during the rope-pulling task. The subjects were free to place their feet but were not allowed to walk during the pulling task.

2.2. Measurement of kinematics and external forces

During all tasks, the subjects were standing on a custom-made 1 × 1 m strain gauge force platform. Prior to the experiment, cuffs constructed of 5 mm thick thermoplastic material (Orfit, Orfit industries nv, Wijnegem, Belgium) had been attached to the lower legs, upper legs, pelvis, trunk, upper arms and lower arms. To each cuff, a 10 × 10 cm metal plate was attached with a double hinge joint. Four LED markers were attached to each metal plate. The hinges allowed positioning the metal plate in such a way that optimal visibility of the markers was guaranteed. A comparable metal plate with hinges was attached to the box for the lifting movements.

Four additional markers (without a cuff) were attached to the head, so that a total of 48 LED markers was used. Movements of the LED's were recorded using a highly accurate (SD < 0.1 mm) automated 3-D movement registration system (Optotrak), with four arrays of three cameras.

Prior to the lifting and pulling tasks, the position of relevant bony landmarks was related to the markers on the cuffs by recording marker positions while an experimenter pointed at the landmarks (Cappozzo, 1990) with a small rigid device containing six LEDs.

During the lifting and pulling tasks, marker positions were recorded at 50 Hz and the force plate data were sampled at 200 Hz. Marker positions were low pass filtered at a cut-off frequency of 10 Hz. A least-squares algorithm (Veldpaus et al., 1988) was used to calculate the transformation of the body segments to their location at each instant during the lifting and pulling tasks. This transformation, together with the recordings of landmark positions were used to reconstruct, for each body segment, its anatomical axes and the center of mass and joint center locations during the lifting and pulling tasks.

Segment masses and moments of inertia were derived with the aid of anthropometric measurements and regression equations described by McConville et al. (1980). A full-body 3-D linked segment model was used to calculate the body center of mass position during the tasks and to calculate the net moments at the L5/S1 joint in all three planes of motion (Kingma et al., 1996).

2.3. Measurement of ship accelerations

Ship floor accelerations were recorded in 3-D at two locations on board of a 120 m frigate. With x = the longitudinal axis (forward is positive), y = the sideward axis (left is positive) and z = the downward–upward axis (upward is positive) the origin defined at the center of mass of the ship, those two locations were at the front deck of the ship ($x = 44.0$ m, $y = 4.5$ m and $z = 7.0$ m) and close to the center of the ship ($x = -5.0$ m, $y = 6.0$ m and $z = 3.0$ m). Accelerations were measured at a sample rate of 10 Hz during 30 min at four combinations of sea-state and sailing direction. For the sailing direction, the direction of propagation of the waves was expressed in the ship axes system, as the angle with the positive x-axis. Sailing directions were 90° (i.e., waves coming from the left, thus propagating to the right) and 150° (waves coming in at an angle of 30° to the left of the forward axis, thus propagating backward to the right). A cubic spline function was used to interpolate the ship acceleration recordings to 50 Hz.

2.4. Simulated addition of ship accelerations to lifting and pulling tasks

For each task a time window of the same size as the duration of the task was taken from the (3-D) acceleration signal. This time window of ship accelerations was then applied to the task that had been recorded in the laboratory in a way that will be described below. Then the time window was shifted 0.2 s to the right and the procedure was repeated. In this way, a total of nearly 9000 time windows with accelerations signals was taken from each of the 30-min acceleration measurements and used to simulate each of the three tasks. This was repeated for the two locations on the ship and the four sea-state/sailing direction conditions. Furthermore, each simulation was performed with the feet of the subject pointing forward, to the right, backward and to the left with respect to the ship, by adapting the axes the ship acceleration signals. Thus, for each of the six subjects, each of the three tasks was simulated about 9000 × (4 orientations) × (4 sea-state/sailing direction combinations) × (2 locations) = 288 000 times.

When the kinematics of the subject with respect to the ship are not influenced by the ship accelerations, as assumed in the current study, the ground reaction force will increase and decrease with the ship acceleration times body mass. A subject, moving with the ship, experiences the ship accelerations as additional gravity-like forces. Therefore, the ship acceleration was incorporated in the ground reaction force as follows:

$$\mathbf{F}'_{\mathrm{g}} = \mathbf{F}_{\mathrm{g}} + m_{\mathrm{b}}\mathbf{a}_{\mathrm{s}}, \tag{1}$$

where $\mathbf{F}_{\mathrm{g}}$ is the measured ground reaction force vector in stationary conditions, $\mathbf{F}'_{\mathrm{g}}$ is the modified ground reaction force, $\mathbf{a}_{\mathrm{s}}$ is the ship acceleration vector, m_{b} is the body and (for the two lifting tasks) load mass. Since body kinematics relative to the ship were assumed to be the same as under stationary conditions, the moment of the ground reaction force relative to the body center of mass ($\mathbf{M}_{\mathrm{COM}}$) was considered unchanged. This moment was calculated according to

$$\mathbf{M}_{\mathrm{COM}} = (\mathbf{r}_{\mathrm{g}} - \mathbf{r}_{\mathrm{COM}}) \times \mathbf{F}_{\mathrm{g}} + \mathbf{M}_{\mathrm{g}}, \tag{2}$$

where $\mathbf{r}_{\mathrm{g}}$ is the vector to the point of application of the ground reaction force, $\mathbf{r}_{\mathrm{COM}}$ is the vector to the body center of mass and $\mathbf{M}_{\mathrm{g}}$ is the ground reaction moment (which is non-zero around the vertical axis only). Eqs. (1) and (2) were used to calculate the new point of application of the ground reaction force ($\mathbf{r}'_{\mathrm{g}}$), using

$$\mathbf{M}_{\mathrm{COM}} = (\mathbf{r}'_{\mathrm{g}} - \mathbf{r}_{\mathrm{COM}}) \times \mathbf{F}'_{\mathrm{g}} + \mathbf{M}_{\mathrm{g}}. \tag{3}$$

Writing Eq. (3) in components, results in three equations that can be solved for the two unknowns (i.e., for the horizontal components of the modified point of application of the ground reaction force, $\mathbf{r}'_{\mathrm{g},x}$ and $\mathbf{r}'_{\mathrm{g},y}$). Furthermore, the ship acceleration ($\mathbf{a}_{\mathrm{s}}$) was added to the (laboratory-recorded) acceleration of each body segment ($\mathbf{a}_i$), to get a valid equation of linear motion:

$$\mathbf{F}'_{\mathrm{g}} = \sum_{i=1}^{p} m_i\mathbf{g} + \sum_{i=1}^{p} m_i\mathbf{a}'_i, \tag{4}$$

where $\mathbf{a}'_i$ is the modified acceleration vector of segment i, m_i is the mass of segment i, $\mathbf{g}$ is the gravity vector and p is the number of segments of the whole body.

The modified forces ($\mathbf{F}'_{\mathrm{g}}$) and accelerations ($\mathbf{a}'_i$), were inserted in an equation of angular motion in the global axis system according to Hof (1992), to calculate the net moment at the lumbo-sacral joint:

$$\begin{aligned}\mathbf{M}_{\mathrm{L5S1}} = {} & -\mathbf{M}_{\mathrm{g}} - (\mathbf{r}'_{\mathrm{g}} - \mathbf{r}_{\mathrm{L5S1}}) \\ & \times \mathbf{F}'_{\mathrm{g}} - \sum_{i=1}^{q}[(\mathbf{r}_i - \mathbf{r}_{\mathrm{L5S1}}) \times m_i\mathbf{g}] \\ & + \sum_{i=1}^{q}[(\mathbf{r}_i - \mathbf{r}_{\mathrm{L5S1}}) \times m_i\mathbf{a}'_i] + \sum_{i=1}^{q} \mathrm{d}(I_iT_i)/\mathrm{d}t,\end{aligned}$$

where $\mathbf{M}_{\mathrm{L5S1}}$ is the net moment at the L5/S1 joint, $\mathbf{r}_{\mathrm{L5S1}}$ is the vector to the L5/S1 joint, $\mathbf{r}_i$ is the vector to the center of mass of each body segment, q is the number of segments of the lower body up to L5/S1, I_i is the inertia tensor of segment i and T_i is the angular velocity vector of segment i. One small modification to the equation described by Hof (1992) is the addition of the ground reaction moment, measured by the force-platform. This moment is non-zero around the vertical axis only. It should be noted again that we ignored angular velocities and angular accelerations of the ship and this causes a small error in the first and last term on the right side of the equation of angular motion. Finally, the moments at the L5/S1 joint were projected onto the pelvic axis system to obtain lateral flexing, extending, and twisting moments.

2.5. Balance considerations

A conservative estimate of the support plane of the feet was defined for each task and subject as follows: a line was drawn from the most posterior point of the calcaneus to the tip of the second toe in both feet. A safety margin in forward–backward direction was taken into account by removing the most forward and most backward 5% of the line for each foot. Then the lines of the left and right foot were connected to form the support plane. Adaptation of the movement pattern to prevent falling was considered to be required when the calculated point of application of ground reaction force would leave the support plane, for one or more samples (i.e., for 20 ms or more).

For each series of simulations, the total number of trials with required movement adaptations was calculated. Summary results of peak net moments at the lumbo-sacral joint were calculated after removal of the trials with required movement adaptations.

2.6. Processing of results

For all tasks that were simulated, the peak total moments and the absolute peak values of the three moment components were stored for further processing. The worst and best cases for each series of 9000 time windows were analyzed by averaging, for each subject, sea-state, sailing direction, subject orientation and location on the ship, and for each of the three lifting/pulling trials, the 99th and 1st percentile of moments for each of the three moment components and for the total moment. For both sea-states separately, ANOVAs were applied with the predicted percentage of trials with required movement adaptations and with the 99th percentile values of the three moment components and the total moment as dependent variables. The independent variables were task, subject, location on the ship, subject orientation relative to the ship and sailing direction.

3. Results

Depending on the sea-state, sailing direction and measurement location, the RMS values of ship accelerations measured midship ranged 0.006–0.127, 0.008–0.584 and 0.015–0.483 m/s^2 for the X, Y and Z directions, respectively. RMS accelerations in all directions as well as the correlation between directions were highly dependent on sea-state, sailing direction and on the location (central or at the front deck) where the acceleration had been measured (Table 1).

X accelerations were largest at the midship location and the accelerations in Y and Z direction were largest at the front deck. Sailing at an angle of 90° caused higher accelerations as compared to sailing at an angle of 150°. The median frequency of the acceleration signals varied between 0.143 and 0.307 Hz and depended mainly on sailing direction and sea-state and, to a lesser extent, on location at the ship (Table 1).

Correlations among signals in different acceleration directions varied over sea-state, sailing direction and the location at the ship (Table 2). Consistently over sea-states and location, X accelerations were positively correlated to Y and Z direction when sailing at an angle of 150° relative to the waves, but negatively correlated to the Y and Z direction when sailing at an angle of 90° relative to the waves.

3.1. Predicted effect of ship acceleration during sea-state 2

During sea-state 2, the sea was rather calm and the RMS accelerations were small, below 0.12 m/s^2. Those accelerations were generally too small to be a potential threat to the whole body balance. The only exception was when sailing at an angle of 90° with respect to the waves, and the subjects would perform a pulling task at the front deck

Table 1
RMS value and median frequency of the x (forward–backward), y (left–right) and z (upward) acceleration, measured at two locations on board of a frigate. These accelerations, measured at a sample rate of 10 Hz during 30 min, were applied to two lifting tasks and one pulling task, in order to calculate the potential effect on low back loading

	RMS X (m/s^2)	RMS Y (m/s^2)	RMS Z (m/s^2)	X median freq (Hz)	Y median freq (Hz)	Z median freq (Hz)
Front deck sea-state 2, 90°	0.006	0.118	0.070	0.303	0.307	0.291
Front deck sea-state 2, 150°	0.004	0.022	0.040	0.184	0.227	0.202
Front deck sea-state 4, 90°	0.028	0.584	0.294	0.223	0.197	0.225
Front deck sea-state 4, 150°	0.098	0.234	0.483	0.143	0.168	0.165
Mid ship sea-state 2, 90°	0.009	0.055	0.062	0.295	0.297	0.281
Mid ship sea-state 2, 150°	0.006	0.008	0.015	0.188	0.248	0.211
Mid ship sea-state 4, 90°	0.039	0.530	0.268	0.221	0.150	0.222
Mid ship sea-state 4, 150°	0.127	0.094	0.173	0.147	0.152	0.161

Table 2
Correlations between the X (forward–backward), Y (left–right) and Z (upward) acceleration, measured at two locations on board of a frigate. These accelerations, measured at a sample rate of 10 Hz during 30 min, were applied to two lifting tasks and one pulling task, in order to calculate the potential effect on low back loading

	R X–Y	R X–Z	R Y–Z
Front deck sea-state 2, 90°	−0.980	−0.431	0.381
Front deck sea-state 2, 150°	0.358	0.647	0.813
Front deck sea-state 4, 90°	−0.688	−0.369	0.003
Front deck sea-state 4, 150°	0.438	0.792	0.813
Mid ship sea-state 2, 90°	−0.816	−0.384	0.055
Mid ship sea-state 2, 150°	0.529	0.536	0.582
Mid ship sea-state 4, 90°	−0.087	−0.292	−0.245
Mid ship sea-state 4, 150°	0.851	0.637	0.671

with the feet pointing forward or backward. For some of the subjects adaptation of the movement pattern to prevent falling would be needed regularly due to the fact that they placed the feet almost in line after one another so that their sideward base of support became quite narrow. It is questionable, however, whether those subjects would position their feet in this unstable way on a ship.

Despite the fact that the accelerations during sea-state 2 are almost 2 orders of magnitude smaller than gravity, the 'worst' case effects in terms of the 1st and 99th percentile peak moment were not always negligible, especially when sailing at an angle of 90° with respect to the waves. In the worst case, the 99th percentile simulations of the asymmetrical lifting movement with the subject standing at the front deck with the feet pointing backward, showed a 6.8 ± 0.9 N m ($15.9 \pm 2.2\%$) increase of the twisting moment. A comparable increase in twisting moment was found for this condition when lifting symmetrically (7.2 ± 1.2 N m), but a lower increase of the twisting moment was found for the pulling task (3.5 ± 0.6 N m).

The 99th percentiles of the extending and total moment at the L5/S1 joint were, relative to their actual value, only marginally increased during sea-state 2. Averaged over subjects, this increase was below 2.5% in lifting for all sailing directions, subject orientations and locations on the ship. For the pulling task, absolute changes were even smaller, but relative changes were slightly higher (up to 4.4%) due to the low extending and total moment during this task. Because of the marginal effects of sea-state 2 accelerations, further results are presented for sea-state 4 only.

3.2. *Predicted effect of ship acceleration on the need to adapt the movement pattern to prevent falling during sea-state 4*

During sea-state 4, a need to adapt the movement pattern to prevent falling was predicted more often during symmetrical lifting than during asymmetrical lifting, and more often during pulling than during lifting. (Table 3 and Fig. 1). Furthermore, the predicted need to adapt the movement pattern was highly dependent on the sailing direction and moderately dependent on the location on the ship. When sailing at an angle of 90°, a need to adapt the movement pattern was predicted for a high percentage of trials (Fig. 1) and this was related to the large

Table 3
ANOVA results for the predicted 99th percentile lateral flexing (Mlat.fl), extending (Mext), twisting (Mtwist) and total (Mtot) moment as well as for the predicted percentage trails with the need to adapt the movement to prevent falling (% adapt)

Independent variables	(DF)	Mlat.fl *p*	Mext *p*	Mtwist *p*	Mtot *p*	% adapt *p*
Location	(1200)	<**0.001**	<**0.001**	<**0.001**	<**0.001**	<**0.001**
Subject	(5200)	<**0.001**	<**0.001**	<**0.001**	<**0.001**	<**0.001**
Rotation	(3200)	<**0.001**	<**0.001**	<**0.001**	<**0.001**	0.055
Sail direction	(1200)	<**0.001**	<**0.001**	<**0.001**	<**0.001**	<**0.001**
Task	(2200)	<**0.001**	<**0.001**	<**0.001**	<**0.001**	<**0.001**
Location × subject	(5200)	0.900	0.006	0.405	0.004	0.914
Location × rotation	(3200)	0.332	0.006	<**0.001**	0.003	0.929
Location × sail direction	(1200)	<**0.001**	<**0.001**	<**0.001**	<**0.001**	0.988
Location × task	(2200)	0.072	<**0.001**	0.001	<**0.001**	0.024
Subject × rotation	(15,200)	0.043	0.284	0.003	0.441	0.004
Subject × sail direction	(5200)	0.004	0.585	<**0.001**	0.197	0.001
Subject × task	(10,200)	<**0.001**	<**0.001**	<**0.001**	<**0.001**	<**0.001**
Rotation × sail direction	(3200)	<**0.001**	<**0.001**	<**0.001**	<**0.001**	0.010
Rotation × task	(6200)	<**0.001**	<**0.001**	<**0.001**	<**0.001**	<**0.001**
Sail direction × task	(2200)	0.057	<**0.001**	<**0.001**	<**0.001**	<**0.001**
Location × rotation × sail direction	(3200)	0.684	0.828	0.003	0.612	0.944
Location × rotation × task	(6200)	0.559	0.003	<**0.001**	<**0.001**	0.242
Location × sail Direction × task	(2200)	0.053	<**0.001**	0.331	<**0.001**	0.049
Rotation × sail direction × task	(6200)	<**0.001**	<**0.001**	<**0.001**	<**0.001**	<**0.001**
Location × rotation × sail direction × task	(6200)	0.955	0.995	0.558	0.895	0.793

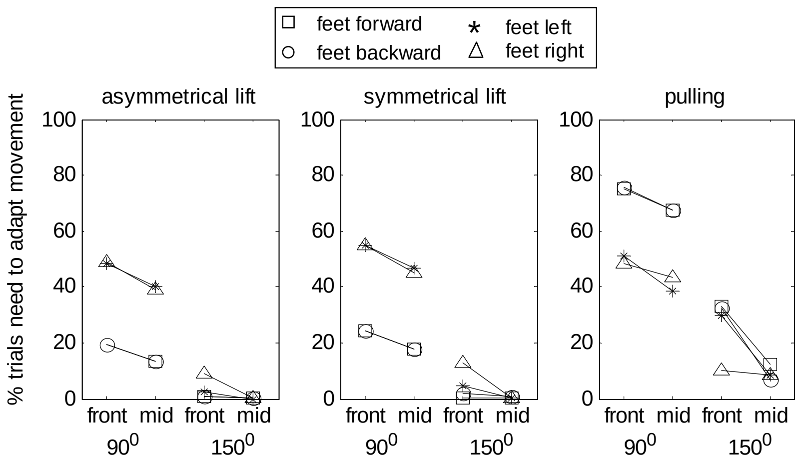

Fig. 1. Effect of ship accelerations at sea-state 4 on the predicted percentage of trials where adaptation of the movement pattern would be needed to prevent falling, during an asymmetrical lifting task (left), a symmetrical lifting task (middle) and a pulling task (right). On the horizontal axis, two locations on the ship (front deck and mid ship) and two sailing directions (90° and 150° with respect to the waves) are indicated. On the vertical axis, the percentage of trials (averaged over subjects) is indicated for which adaptation of the movement pattern to prevent falling would be needed during 30 min sailing. The symbols indicate different subject orientations with respect to the ship.

sideward (Y) acceleration at this sailing angle (Table 1). In the worst case, when performing the pulling task at the front deck, a need to adapt the movement pattern was predicted in about 75% of the trials when the feet would be pointing forward or backward. During lifting, the most frequent need to adapt the movement pattern was also predicted when working at the front deck and sailing at an angle of 90°, but now with the feet pointing either left or right (43% for asymmetrical lifting and 53% for symmetrical lifting). In both lifting tasks and both locations, the predicted percentage of trials with the need to adapt the movement pattern was over twice as large when the feet pointed sideward compared to when the feet pointed forward or backward. Conversely, during pulling, the predicted percentage of trials with need to adapt the movement pattern was over 50% larger when the feet pointed forward or backward compared to when the feet pointed sideward. Likewise, the task also interacted with location on the ship and with sailing direction (Table 3). These interactions are related to the effect of sailing direction, location on the ship (Table 1) and subject orientation on the ratio between forward–backward and lateral acceleration relative to the subject, in combination with the wider (but shorter) base of support during lifting and the longer (but narrower) base of support during pulling (where subjects placed their feet in straddle position).

3.3. Predicted effect of ship acceleration on low back loading in case of unfavorable timing during sea-state 4

After removal of all trials with predicted need to adapt the movement pattern, the predicted effect of 'bad timing' from the perspective of low back loading, was estimated by calculating the 99th percentile of predicted peak moments at the L5/S1 joint for each series of 9000 time windows. This was done separately for each plane of motion. Subsequent ANOVAs on those 99th percentile values showed a main effect of all independent variables (i.e., subject, location on the ship, orientation of the subject, task and sailing direction) on the moments in all three planes of motion as well as on the total moment (Table 3). In addition, there were many significant interactions between the independent variables (Table 3).

With respect to the extending and total moment during the lifting tasks, the 99th percentile peak moments only exceeded the peak moments without ship acceleration by more than 10% when the subjects would be standing at the front deck and the ship would be sailing at an angle of 150° with respect to the waves (Fig. 2). In the worst case, lifting asymmetrically with the feet pointing to the left, the 99th percentile peak extending moment would be 33.9 ± 5.7 N m (13.4 ± 2.3%) higher than the peak extending moment without ship acceleration. For the extending and total moment, the effect of subject orientation was quite small. However, the twisting moment was highly affected by subject orientation (Fig. 2). Especially when sailing at 90°, lifting with the feet pointing forward or backward caused a large increase of the 99th percentile peak twisting moment (up to 28.4 ± 5.5 N m or 66.7 ± 12.9% when lifting asymmetrically at the front deck). This shows the 'cost' of preventing balance problems by standing with the feet forward or backward when there are large sideward accelerations.

Compared to the twisting moment, the lateral flexion moment was relatively unaffected by ship accelerations in all three tasks. The maximum change of the 99th percentile peak lateral flexing moment was 9.6 ± 4.2 N m (when lifting symmetrically at the front deck with the feet pointing to the right and the ship sailing at an angle of 90° with respect to the waves).

For the pulling task, relative changes in extending moment were up to 14.0 ± 6.7%. However, as can be seen in Fig. 2, the peak extending moment without ship acceleration as well as the absolute magnitude of the effect of bad timing was much smaller in the pulling task as compared to the lifting tasks.

3.4. Predicted back load reduction in case of favorable timing during sea-state 4

Potentially, good timing might result in a decrease of low back loading during lifting or pulling on a ship. First, for each series of 9000 time windows, the number of time windows was

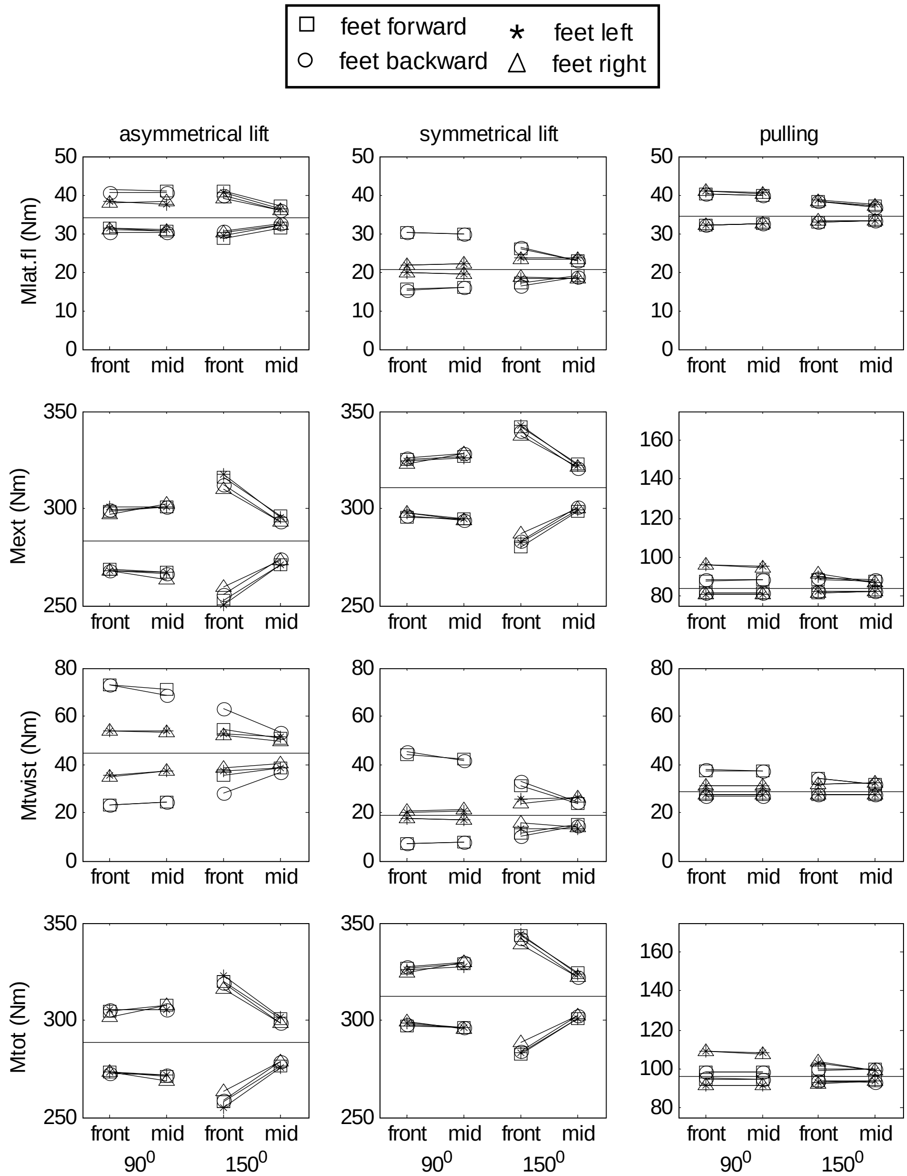

Fig. 2. Effect of ship accelerations at sea-state 4 on the predicted 1st and 99th percentile moment at the L5/S1 joint during an asymmetrical lifting task (left), a symmetrical lifting task (middle) and a pulling task (right). On the horizontal axis, two locations on the ship (front deck and mid ship) and two sailing directions (90° and 150° with respect to the waves) are indicated. On the vertical axis, the lateral flexing moment (Mlat, 1st row), extending moment (Mext, 2nd row) twisting moment (Mtwist, 3rd row) and total moment (Mtot, 4th row) are indicated. The symbols indicate different subject orientations with respect to the ship. In each graph, the horizontal solid line indicates the net moment (averaged over subjects) that was measured during the task performed without ship accelerations.

counted that satisfied the condition that adaptation of the movement pattern to prevent falling would not be needed and the peak total moment at the L5/S1 joint would not be increased in comparison to peak total moment under stationary conditions. Averaged over locations and subject orientations, it turned out that for asymmetrical lifting, 34.2 ± 3.8% of the trials would result in reduced low back loading and no need to adapt the movement pattern when sailing at an angle of 90° with respect to the waves and 48.7±1.2% would result in reduced low back loading when sailing at 150°. For symmetrical lifting, those numbers were 31.4±6.2% and 48.2±1.3%, respectively. For the pulling task, only 8.3±4.7% and 29.1±8.4% would result in reduced low back loading and no need to adapt the movement pattern when sailing at an angle of 90° and at an angle of 150°, respectively. Fig. 3 shows that, for all tasks, particularly the pulling task, the percentage of remaining trials quickly dropped to zero when the total net moment were constrained to be reduced with a substantial percentage, e.g. 10%. This held for all subjects, both locations on the ship, all orientations and both sailing directions (Fig. 3).

4. Discussion

In the current simulation study, low back load and the percentage of trials where movement adaptations would be needed to prevent falling was predicted during two lifting tasks and one pulling task on a large ship. When the sea was quiet (sea-state 2) only a small increase in low back

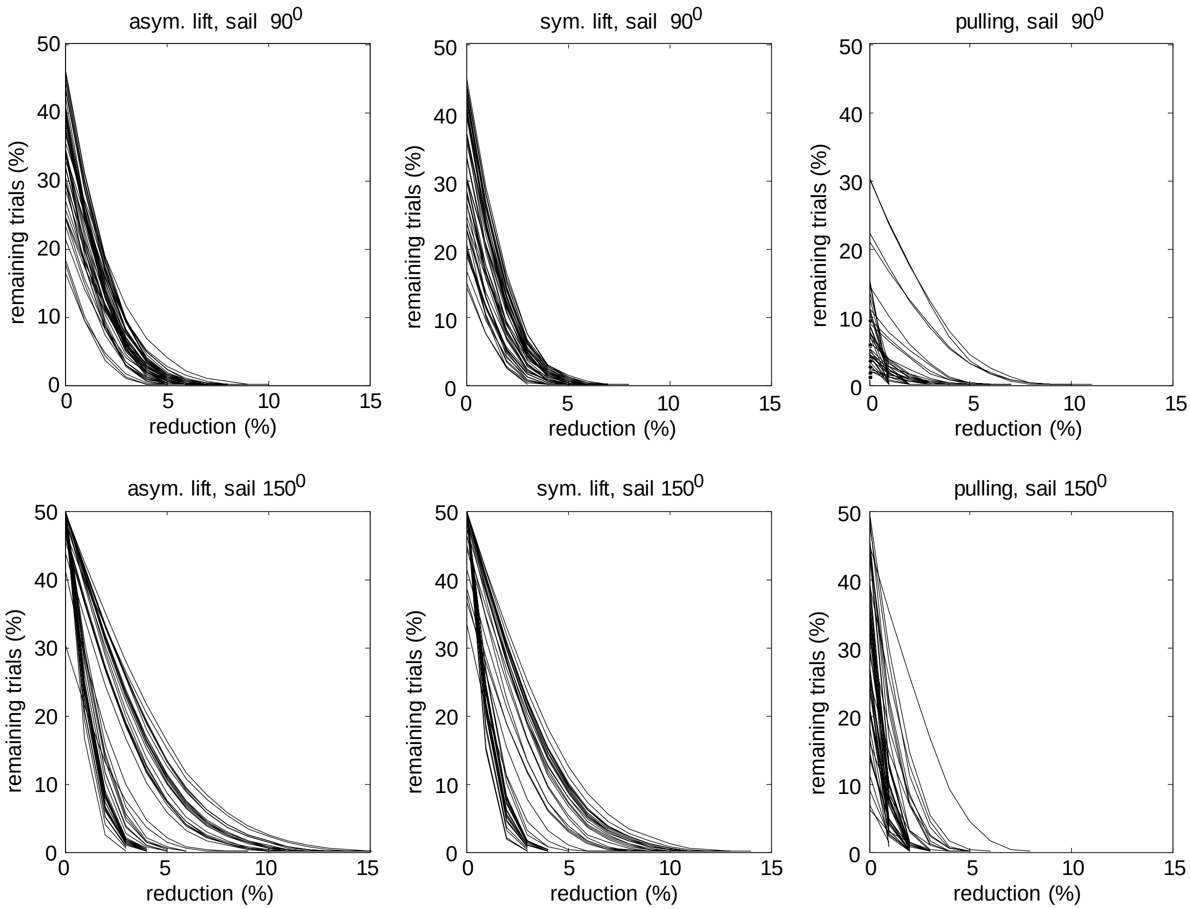

Fig. 3. The predicted percentage of trials (vertical axis) that would remain during asymmetrical lifting (left), symmetrical lifting (middle) and a pulling task (right), under the assumption that subjects would time their task in such a way that the total moment at the L5/S1 joint would be decreased with a certain percentage (horizontal axis). Each line indicates one subject, in one orientation and sailing direction. The top row is the front deck and the bottom row is the midship location on the ship.

loading was found when the worst cases (99th percentile moments) were analyzed. The need to adapt the movement pattern to prevent falling was predicted in only a small number of trials. During sea-state 4, the 99th percentile moments were still only moderately affected (up to 14%) when looking at the extending moment or at the total moment. However, relative to its normal value without ship accelerations, the twisting moment was affected much stronger, up to 66.7% during asymmetrical lifting at the front deck, with the feet pointing forward or backward, and sailing at an angle of 90° with respect to the waves. The resulting twisting moment for that condition (on average 73.6 N m) was about 75% of the maximum isometric twisting moment that males can produce and over 100% of the maximum isometric twisting moment that females can produce in upright stance (Parnianpour et al., 1988; McGill and Hoodless, 1990). A further increase of the twisting moment might be expected for 60° or 90° asymmetrical lifts (Kingma et al., 1998; Marras and Davis, 1998). Although asymmetrical moment components do not necessarily lead to increased lumbar compressive forces in upright standing posture (van Dieën and Kingma, 1999), asymmetrical low back loading combined with asymmetrical trunk bending movements does lead to increased spinal compression during lifting (Marras and Davis, 1998). For twisting moments, moment arms of the muscles are relatively small. Furthermore, epidemiological research suggests that twisting movements are a separate risk factor for the occurrence of low back pain (Hoogendoorn et al., 2000) and acute lumbar disc prolapse (Kelsey et al., 1984). The current simulation results suggest that this risk may be further increased when working on a ship. Furthermore, the current study may well underestimate low back loading during lifting on a ship. Firstly, angular accelerations were not taken into account. However, those are likely small on a large ship. We did take the major effect of angular motion (i.e. the change of the orientation of the gravity vector relative to the ship surface) into account. Secondly, we used accelerations on a large ship, which are generally smaller as compared to accelerations on a smaller ship. On a smaller ship, low back loading might thus be further increased. However, the current method would not be suitable to predict this effect, since larger accelerations would cause balance problems in a majority of the trials, when the body posture and movement relative to the ship surface would not be adapted. Subjects would therefore have to adapt their posture and this would violate the assumptions in the current study. It is known that posture adaptations on a ship mainly occur in the ankle and knee joint (Törner et al., 1994). Törner et al. (1994) performed a sagittal plane analysis of fishermen during actual working conditions on a trawler with a length of 24 m. During upright stance while holding a 21 kg load, they found a 40% increase of lumbar moments, in comparison to the same task without ship acceleration. During lifting, they found peak lumbar moments up to 310 N m. This is lower than the 99th percentile peak moments that we predicted, despite the use of a 21 kg load in comparison to our 15 kg load. This may be related to the starting position of the load relative to the body, or to the avoidance of lifting during 'worst case' accelerations.

Our analysis of favorable timing showed that it is almost impossible to time lifting and pulling movements in such a way that a substantial (>10%) reduction of the total low back moment is obtained. On the other hand, one might wonder whether the worst case scenario, adopted in the current study by taking the 99th percentile moments, is a realistic prediction of the actual peak work load. Theoretically, one could avoid peak loading, such as reflected by the 99th percentile values, by appropriate timing. Therefore, the 99th percentile may be an overestimation of actual peak loading. However, guidelines concerning lifting are, at least for low lifting frequencies, based on peak compressive spinal loads (Waters et al., 1993; van Dieën and Toussaint, 1997), which implies that, when many peaks occur, one should especially consider the peak of the peaks. Furthermore, compressive forces may be increased during manual materials handling on a ship due to the need for stabilizing co-contractions. The increased oxygen consumption of subjects standing on a ship during a static weight holding task (Törner et al., 1988), and the reduced capacity to take up oxygen (Wertheim et al., 2002) indeed hint in the direction of an increased overall muscular tension during work on a ship.

From the perspective of designing tasks on a ship, the current results suggest that lifting as well as pulling tasks can better be placed at the midship than at the front deck location. The need to adapt the movement pattern was, for all cases studied, less frequently predicted at the midship location. This does not imply that the risk of falling is lower at that location, but that less frequently adaptation of the lifting movement to prevent falling is required at that location. The worst cases of back loading in terms of total moments, lifting at the front deck when sailing at 150°, can be avoided when the task is performed at the midship location.

Another variable that can be influenced by design is the orientation of the subject during task execution. Back load considerations would suggest that the best orientation of the feet is pointing sideward because a substantial increase in twisting moment is predicted when the feet would be pointing forward or backward. However, balance considerations show that adaptation of the lifting movement to prevent falling is more often needed when the feet are pointing sideward compared to the feet pointing forward or backward. It is unclear how this would affect back loading.

Quantification of the 3-D back load in experienced sailors, during actual working conditions on a ship, is needed to find out whether the advantage of the feet pointing sideward in terms of low back loading outweighs a possible disadvantage due to compensatory movements to preserve balance. This points at another limitation of the current study: the risk of falling can only be investigated by actually measuring manual material handling tasks on a ship or in a simulator that can produce realistic acceleration patterns. The current simulations also do not allow inferences regarding the effect of movement pattern adaptations (to prevent falling) on low back loading. The current predictions of the influence of ship accelerations on low back loading are likely to be valid for relatively low levels of ship acceleration, where adaptations of the movement pattern are likely to be small, but this still needs verification under actual working conditions on a ship.

Acknowledgements

We would like to acknowledge the Royal Netherlands Navy for partially funding this study, MARIN (Maritime Research Institute Netherlands) for providing ship acceleration data, and Wiebe de Vries for performing the laboratory experiments.

References

Cappozzo, A., 1990. Joint kinematic assessment during physical exercise. In: Berme, N., Capozzo, A. (Eds.), Biomechanics of Human Movement: Applications in Rehabilitation, Sports and Ergonomics. Bertec, Worthington, OH, pp. 263–274.

Hof, A.L., 1992. An explicit expression for the moment in multibody systems. Journal of Biomechanics 25, 1209–1211.

Hoogendoorn, W.E., Bongers, P.M., de Vet, H.C., Douwes, M., Koes, B.W., Miedema, M.C., Ariens, G.A., Bouter, L.M., 2000. Flexion and rotation of the trunk and lifting at work are risk factors for low back pain: results of a prospective cohort study. Spine 25 (23), 3087–3092.

Kelsey, J.L., Githens, P.B., White, A.A., Holford, T.R., Walter, S.D., O'Connor, T., Ostfeld, A.M., Weil, U., Southwick, W.O., Calogero, J.A., 1984. An epidemiological study of lifting and twisting on the job and risk for acute prolapsed lumbar intervertebral disc. Journal of Orthopaedic Research 2 (1), 61–66.

Kingma, I., de Looze, M.P., Toussaint, H.M., Klijnsma, J.G., Bruijnen, T.B.M., 1996. Validation of a full body 3-D dynamic linked segment model. Human Movement Science 15, 833–860.

Kingma, I., van Dieën, J.H., de Looze, M.P., Toussaint, H.M., Dolan, P., Baten, C.T.M., 1998. Asymmetric low-back loading in asymmetric lifting movements is not prevented by pelvic twist. Journal of Biomechanics 31 (6), 527–534.

Marras, W.S., Davis, K.G., 1998. Spine loading during asymmetric lifting using one versus two hands. Ergonomics 41 (6), 817–834.

McConville, J.T., Churchill, T.D., Kaleps, I., Clauser, C.E., Cuzzi, J., 1980. Anthropometric relationships of body and body segment moments of inertia. Air force aerospace medical research laboratory, Wright-Patterson Air Force Base, Ohio, AFAMRL-TR-80-119.

McGill, S.M., Hoodless, K., 1990. Measured and modelled static and dynamic axial trunk torsion during twisting in males and females. Journal of Biomedical Engineering 12 (5), 403–409.

Parnianpour, M., Nordin, M., Kahanovitz, N., Frankel, V., 1988. 1988 Volvo award in biomechanics. The triaxial coupling of torque generation of trunk muscles during isometric exertions and the effect of fatiguing isoinertial movements on the motor output and movement patterns. Spine 13 (9), 982–992.

Törner, M., Blide, G., Eriksson, H., Kadefors, R., Karlsson, R., Petersen, I., 1988. Musculo-skeletal symptoms as related to working conditions among Swedish professional fishermen. Applied Ergonomics 19 (3), 191–201.

Törner, M., Almstrom, C., Karlsson, R., Kadefors, R., 1994. Working on a moving surface-a biomechanical analysis of musculo-skeletal load due to ship motions in combination with work. Ergonomics 37 (2), 345–362.

van Dieën, J.H., Kingma, I., 1999. Total trunk muscle force and spinal compression are lower in asymmetric moments as compared to pure extension moments. Journal of Biomechanics 32 (7), 681–688.

van Dieën, J.H., Toussaint, H.M., 1997. Evaluation of the probability of spinal damage caused by sustained cyclic compression loading. Human Factors 39 (3), 469–480.

Veldpaus, F.E., Woltring, H.J., Dortmans, L.J.M.G., 1988. A least squares algorithm for the equiform transformation from spatial marker coordinates. Journal of Biomechanics 21 (1), 45–54.

Waters, T.R., Putz-Anderson, V., Garg, A., Fine, L.J., 1993. Revised NIOSH equation for the design and evaluation of manual lifting tasks. Ergonomics 36 (7), 749–776.

Wertheim, A.H., 1998. Working in a moving environment. Ergonomics 41 (12), 1845–1858.

Wertheim, A.H., Kemper, H.C., Heus, R., 2002. Maximal oxygen uptake during cycling is reduced in moving environments; consequences for motion-induced fatigue. Ergonomics 45 (3), 186–202.